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**SOME CONTRIBUTIONS TO ENERGETICS BY THE LEWIS
RESEARCH CENTER AND A REVIEW OF THEIR
POTENTIAL NON-AEROSPACE APPLICATIONS**

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SOME CONTRIBUTIONS TO ENERGETICS BY THE LEWIS RESEARCH CENTER AND A REVIEW OF THEIR POTENTIAL NON-AEROSPACE APPLICATIONS

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ABSTRACT

The primary technology areas of the Lewis Research Center are aerospace propulsion, power and materials. As examples in these technologies, the authors review the Center's programs in the fields of cryogenics and liquid metals. Potential non-aerospace application for the results of these programs are discussed. These include such possibilities as: hydrogen as a non-polluting industrial fuel; more efficient central power stations and powerplants for advanced ground transportation.

INTRODUCTION

This paper reviews some of the aerospace research and development at the Lewis Research Center which can be classified under the general heading of "Energetics." Most of the R & D done at Lewis could be placed in this category because the Center has the NASA responsibility for propulsion, energy conversion, and materials.

The propulsion research involves airbreathing engines, chemical rockets, electric thrusters, and nuclear rockets. The effort in energy conversion includes batteries, fuel cells, thermionic converters, photovoltaic cells, magnetohydrodynamics, and Rankine and Brayton cycle systems. The materials program includes applications for high temperature, for cryogenic use and such exotic materials as metal-polymer matrix composites. We have chosen to focus on two topics; namely, cryogenics and liquid metals with which we have been personally involved. First, we will present a review of the work that has been done or is in progress in these areas as part of NASA's aerospace effort. This will be done by highlighting some of the programs and citing a part of the significant technical literature which detail the work in these programs. Then, in response to the theme of this session, we will comment on the applicability of this work to several non-aerospace problem areas.

CONTRIBUTIONS TO CRYOGENICS

In the late 40's and early 50's the Lewis Research Center was involved in a research program to select optimum high energy fuels and oxidizers suitable for jet propulsion applications. From known theoretical thermochemical performance, liquid hydrogen ranked high on the list of fuels. Once a rare laboratory curiosity, liquid hydrogen became available in sufficient quantities for fuel research largely as a result of the U.S. intensive thermo-

nuclear research and development of the '40's. The National Bureau of Standards, the Atomic Energy Commission, the Department of Defense, and many private contractors including universities, had contributed to highly developed techniques for producing, handling and storing liquid hydrogen.

Fuel Research

The turbojet work with liquid hydrogen was done as a flight research program in a B-57 aircraft which was specially fitted and modified for the program. Figure 1 is a photograph of the aircraft. It was concluded from this study (1) that it is feasible to fuel an operational aircraft with hydrogen.

Studies of hydrogen for chemical rockets began even before the turbojet program. This effort proved to be significant and timely. It was one of the earliest programs to evaluate the problems and potentials of hydrogen-fueled rockets. Hydrogen proved to be unusually well behaved as a liquid fuel. It burned stably and efficiently over broad limits of fuel/oxidant ratios (2,3). There were some unusual and difficult problems with the oxidizers used in conjunction with hydrogen. Liquid oxygen was a cryogen that required special handling in scrupulously clean hardware. Fluorine was nastier yet in terms of its compatibility with flow systems and storage vessels. Elaborate procedures had to be followed to condition the flow system against complete oxidation by the fluorine. The "pickling" process was tedious and didn't always insure that the oxidizer would stay contained in the system as intended.

In any case, hydrogen with either of these oxidizers was, and still is, the most energetic liquid chemical propellant combination known. The technology advanced sufficiently during the 1950's to make hydrogen one of the fuels selected for space missions in the 1960's.

A decision was made in 1961 to utilize hydrogen as a fuel in the upper stages of the Apollo vehicle for the moon-landing mission. The pioneering rocket studies with hydrogen years before NASA came into being proved to be influential in reaching this decision.

Measurement and Pumping

Interest in hydrogen as a propellant was the motivation for some research relating to the handling and usage of the fuel in propulsion systems. Included in this research was a separate program on instrumentation. For example, the Lewis Research Center

has been active in the application of carbon and platinum resistor temperature gages (4). Also in conjunction with the early rocket thrust stands, the use of turbine-type flow meters for hydrogen service was developed (5). More recently, a new method for determining the density of liquid and two phase hydrogen has been devised (6).

Pumping of hydrogen was another research area. In the pumping of liquids, one of the primary concerns is encountering cavitation on the impeller vanes. Cavitation generally leads to severe loss of performance and even to physical damage of the pump. It was learned that in the case of liquid hydrogen, there was considerably more operational margin before cavitation effects on performance were noted. The Lewis Research Center developed practical design criteria to allow hydrogen pump designers to incorporate this added cavitation margin into their designs (7).

Fluid Properties

Physical and transport property data for hydrogen were very scanty when these programs with hydrogen were initiated during the 1950's. Consequently, it was necessary to acquire a more comprehensive set of property data. Through a contract, the National Bureau of Standards was engaged in an extensive program of property acquisition and correlation (8). The Bureau of Standards also continued to make valuable contributions to the measurement and handling techniques for liquid hydrogen.

Heat Transfer

Another research program with hydrogen was an investigation of the heat transfer and flow characteristics of the fluid. Figure 2 is a phase diagram of the fluid on the temperature entropy plane. The region (region III) underneath the saturation line dome represents the two-phase state. To the left of the dome is a compressed liquid region (region II); to the right is a gaseous or vapor region (region Ia); just above the apex of the dome is the near-critical state region IV; and further above that, the fluid behaves like a gas (region I).

The objective of the program was to investigate the heat transfer characteristics of hydrogen over the entire domain of fluid states. In a propulsion system, several of these fluid states are encountered. The program began with a study of the two-phase domain and continued into the near-critical and then high-pressure gas regions. The apparatus consisted of an electrically heated tubular test section and a tank which pressure-fed the hydrogen through the test section. Many channels of instrumentation were employed in measuring the heat transfer rates, the fluid and wall temperatures, the flow rates and pressures of the fluid.

In the two-phase region (region III, fig. 2), a film boiling situation was encountered which was unique when compared to experiences with other fluids. A correlation for the local heat transfer and pressure drop was developed (9). Besides the convective boiling, the pool boiling of liquid hydrogen was studied. The experiments encompassed nucleate and film boiling processes and such factors as body forces (gravity) and geometry were parameters of the program (10). It was observed that hydrogen will

begin to boil on surfaces when subjected to temperature differences less than one degree Fahrenheit.

Following the two phase studies in the heated tube apparatus, hydrogen in its near-critical state was examined. It was discovered that the heat transfer of near critical hydrogen resembled that of the two phase region and that conventional forced convection correlations were greatly in error (11).

The liquid hydrogen programs pursued at Lewis during the 1950's and 1960's contributed information which was utilized by NASA and its contractors in the design and successful operation of liquid hydrogen engines. Hydrogen will continue to hold an important place in future space flight missions.

Current Research

In the cryogenic area, two of the programs now underway at the Lewis Research Center will be discussed. The first is an attempt to systematize the available fluid properties of the cryogenics so that one consistent, authoritative source of information is available throughout NASA. The Lewis Research Center is conducting this program in conjunction with the National Bureau of Standards. Fluid properties (including transport properties) are now available in useful computer codes that are adaptable to a variety of applications (12, 13).

The second program is directed at investigating the choked flow characteristics of cryogenics. Following the Apollo 13 accident in which liquid oxygen leaked out of a rupture in one of the main supply tanks, the question of estimating discharge rates for such a fluid was raised. Preliminary computational methods are compared with experimental choked flow rates for a two-phase cryogen (14.). Current research is directed at a general analytical method for estimating choked flows of cryogenics.

CONTRIBUTIONS TO LIQUID METAL TECHNOLOGY

Since 1960 the Lewis Research Center has had primary NASA responsibility for development of electric power systems for use in space. Through a coordinated in-house and contractual effort both dynamic and static (direct) energy conversion systems were studied. The operating temperatures of some of these space systems are well above those of terrestrial central power stations. Hence, the "exotic" liquid metals (mercury, potassium, sodium, lithium, etc.) were selected as the working fluids and coolants. These selections were based on the liquid metals' relatively low vapor pressures, high thermal conductivities and chemical stability. Results achieved in the development of the liquid metals technology will be illustrated by briefly describing the status of the potassium Rankine space electric power system. The potassium technology is discussed further in references 15 and 16.

Materials Compatibility

Tantalum and niobium-based refractory alloys were selected as containment materials for the high temperature portions of the potassium system because of their high strength and ductility and ease of fabrication and joining (17, 18, 19, 20). They are, however, susceptible to oxidation in air at elevated temperatures. Therefore, these materials must be protected by enclosure in vacuum chambers capable of operating at pressure levels of about 10^{-8} torr.

The long-term compatibility of the candidate alloys exposed to the alkali liquid metals was determined in two corrosion test loops built under contract by Nuclear Systems Programs, General Electric Company (21-25). Each of these loops was comprised of a reactor coolant and a potassium boiling-and-condensing circuit, see figure 3. An electric heater of 10 KW capacity substituted for the reactor heat source, and a simulator rather than a turbine, was installed at the boiler exit. Analyses conducted after these tests demonstrated no generalized corrosion of either the Nb-1Zr or T-111 materials in contact with the high temperature (about 1360 K) liquid metals, attesting to the excellent compatibility of these refractory alloys.

Nuclear Heat Source

Efforts to develop the technology for a lithium-cooled, compact, fast spectrum nuclear reactor of the type required for the potassium Rankine system have recently begun as an in-house project at Lewis. Ceramic uranium mononitride has been selected as the fuel due to its high thermal conductivity, melting point and uranium content. The candidate cladding material is T-111. A reference design of this reactor calls for a 2 MW_t output for 50,000 hours at an outlet temperature of 1220 K (26). Efforts are underway in materials compatibility, irradiation effects, bearings and seals, reactor physics and reactor control. Reference 27 presents a detailed discussion of the materials programs for this reactor. A brief discussion of the irradiation program is as follows.

Miniature fuel elements clad with T-111, Nb-1Zr, W-25 Re-30 Mo and stainless steel will be irradiated at selected temperatures in the range 830 to 1370° C. The burnup rate for these experiments will be accelerated 5 to 10 times that of the reference design. Selection of clad material and temperature level will place the fuel in a relatively restrained, a partially restrained or an unrestrained condition. The measured diametral swelling will be compared with predictions made by analytical models. A second series of accelerated burnup rate tests will be conducted with thinner-clad, full or near full size fuel pins to more directly confirm the fuel element design. Other irradiations in reactors will explore fuel swelling effects with pins containing UO₂ and porous UN fuel and using T-111 and Nb-1Zr as clad materials. Finally, fast neutron irradiations of a series of unfueled clad and structural materials, including tantalum, molybdenum and tungsten based alloys, will be conducted at elevated temperatures. Previous exposure of materials to fast-spectrum neutrons have demonstrated the generation and growth of voids. The voids result in swelling and embrittlement, a major obstacle to the achievement of a long-life fuel element. The materials irradiation tests to be conducted will yield information on changes in mechanical properties, density, chemistry and microstructure.

Turbine

In potassium as well as steam Rankine turbines, condensation or the formation of liquid drops, usually occurs during the vapor expansion process. The constant impact of these droplets, particularly on the rotating members of the latter stages of the turbine, could result in material removal, loss of performance and eventual failure. To assess the significance of moisture erosion on turbine life, two potassium turbines were built and tested at an inlet temperature level of about 1500° F (1100 K),

a level typical of the temperature of the vapor flowing in the latter stages of the space system turbine (28, 29, 30). The first turbine was operated for 5000 hours at a moisture level of 3 percent entering (8 percent leaving) the last of two rotating stages. Subsequently, a three-stage potassium turbine (shown in fig. 4) was tested for an identical period of time with a moisture level of about 7 percent entering the third stage (13 percent leaving).

The erosion damage to the blades of the first turbine was found to be negligible. Examination of the blades of the last stage of the 3-stage turbine indicated the microscopic beginnings of erosion pitting at blade tips. This result, when extrapolated, suggested the need for condensate removal devices, such as those employed in conventional steam power plants. Consequently, the three-stage potassium turbine was reassembled incorporating rotor and stator moisture removal devices. In addition, a vortex condensate separator was installed at the turbine exit. This latter device was representative of a separator which might be installed in the ducting between the two spools of a space system turbine. The effectiveness of these devices with potassium vapor at about 1500° F (1100 K) was found comparable to moisture separation units employed in conventional steam turbines (31).

Boiler

The initial efforts to develop the technology for the boiler were directed at obtaining potassium boiling heat transfer and pressure loss data in once-through single tubes at temperatures up to 1750° F (1230 K) (32), and up to 2100° F (1420 K) (33). The tests were conducted with inserts inside the tubes which caused the boiling potassium to swirl. Analysis of the data indicated the presence of three distinct two-phase heat transfer regimes in a potassium boiler: a nucleate boiling regime in which the tube wall is believed fully wetted; a transition boiling regime in which the wall is only partially wetted; and a superheat region where the tube wall is essentially dry but the vapor may contain tiny droplets. The swirl inserts were found to extend the nucleate boiling regime to higher vapor qualities than possible in a plain tube, thereby reducing the length of the transition region. In addition, the helical flow induced by the inserts enhanced the heat transfer in both the transition and superheat regions. These benefits permitted very compact boiler design, an important requirement for space.

Based on the results just described, a full-scale, multiple-tube potassium boiler was designed (34). One tube of this boiler was fabricated of T-111 and tested over a range of temperatures between 1700° F (1200 K) and 2100° F (1420 K), exit superheats as high as 300° F (167° C) and power inputs between 60 and 185 kW_t (90 kW_t design) (35). Lithium, flowing countercurrent to the potassium in an external annular jacket, served as the heating fluid. The boiler was found to be extremely stable even during transient operations simulating startup. Preliminary analysis of the data indicates that the procedure employed to design potassium boilers with swirl-flow inserts is very accurate (36, 37).

Other Components

Lewis has also sponsored efforts to develop the technology for the other components of liquid metal systems. Several potassium condensers were tested successfully (38, 39). An electromagnetic boiler feed pump cooled by NaK at 800° F (700 K) was tested

for 10,000 hours without degradation (40). Isolation and throttle valves of 1-inch nominal size have been built and tested in flowing lithium for 5000 hours (3500 hours at a temperature of 1900° F (1300 K) (41). Finally, an electrically-actuated throttle valve of 1½-inch nominal size was operated for 5000 hours while frequently exposed to potassium vapor at 2100° F (1420 K) (37). A photograph of this valve is shown in figure 5.

APPLICATIONS

In the previous section, we have reviewed some of the research and development work in cryogenics and liquid metals that has been done, or is in progress, at the Lewis Research Center. As has been indicated, all of this work is directed toward aerospace propulsion and power applications. Next we will suggest some non-aerospace areas where the results of this work could be useful.

Cryogenic Use in Electrical Equipment

A promising area for the application of cryogenic technology is in the production and transmission of electricity. The electrical resistivity of pure metals such as aluminum and copper is dramatically reduced at cryogenic temperatures. For instance at liquid hydrogen temperatures, the resistivity is approximately 1/500 that of the room temperature resistance. Cryogenic resistive transmission cables are being considered for large capacity (200 MW) transmission (42).

Design proposals have been made to build electrical generators and transformers with cryogenically-cooled conductors. According to reference 43, hydrogen cooled aluminum conductors appear to have attractive design characteristics.

Superconducting magnets are being built which employ niobium-tin, niobium-zirconium, or niobium-titanium alloys as the winding material. These conductors are cooled to liquid helium temperatures (4.2 K). At this extremely low temperature, these conductors exhibit practically zero electrical resistance. Superconducting magnets have been manufactured with field strengths as great as 15 Teslas (44).

They are being used in nuclear accelerators and bubble chambers and in research facilities for magnetohydrodynamic and thermonuclear (fusion) studies. It appears that they will have important application to the electric-power generation system of the future. Also, they are being considered as a possible means of levitating vehicles for surface travel.

Hydrogen as a Fuel

Because of the high depletion rate of our fossil reserves, some studies (45) suggest that hydrogen could be used as a fuel and also as a basic raw chemical for domestic and industrial use in place of oil and natural gas.

As part of a study of turbine engines for high-speed trains and buses for the Department of Transportation, the Lewis Research Center is examining the use of hydrogen as a fuel. Hydrogen is particularly attractive for domestic vehicles because of its clean combustion products. Significant amounts of hydrogen could be made available from the electrolysis of water. The electrical power to perform the electrolysis could come from large nuclear-fission powerplants. Some are even looking further ahead to the advent of fusion-electric power and are suggesting that nuclear parks would be constructed along the coastal waters where both electrical power and hydrogen would be produced as basic energy commodities (46). Engineering-economic studies show that transmission of energy over long distances (> 350 mi.) can be done more economically by means of fluids in pipe lines rather than by high-voltage electric transmission lines (45). The existing pipe line system for natural gas could probably be adapted to the transport of hydrogen. Such a proposal poses a number of serious technical problems. One of the most serious is the safety problem. Hydrogen in air has extremely broad explosive limits (18.3% to 59%) and is prone to leak. In these regards it is more difficult to deal with than natural gas, and the safety procedures would have to be more strict, safety-wise. Also, because of hydrogen's low density, flow control equipment, pipe and valve sizes and burner designs would have to be modified. The broad experience with this fuel in the space program should aid in expediting use of hydrogen for domestic purposes. How rapidly and how extensively hydrogen utilization will evolve is not clear at this time.

Non-aerospace Applications of the Liquid Metal Technology

The liquid metals and potassium Rankine technology developed for space will likely find broad terrestrial use. In central station power generation, a lower temperature version of the potassium Rankine system has been proposed as a topping or binary cycle for conventional fossil-fueled steam powerplants (47). Interest in a similar alkali metal binary cycle has been expressed by the Department of Interior (48). The potassium topping cycle when combined with a steam cycle results in an increase in conversion efficiency from the 40 percent level of modern combustion steam powerplants to 50 percent or more. Consumption of fuel, stack emissions and waste heat release are all substantially reduced per unit of electrical power produced by such a plant. A potassium-steam binary cycle has also been proposed as the conversion system for fusion power (49). Depending on potassium turbine inlet temperature, such a powerplant could produce electricity

with an efficiency exceeding 55 percent.

When fusion power is realized, mankind will have an energy source which relies on a virtually unlimited source of fuel. The fusion reaction considered most likely to be demonstrated first is the deuterium-tritium (D-T) reaction. A powerplant utilizing the D-T reaction will require lithium, either in the form of a liquid metal or molten salt, as a coolant and as a material for breeding tritium. To contain the lithium, niobium- and tantalum-based refractory alloys have been suggested. The practicality of such a fusion system will depend considerably on the availability of fully-developed, fully-proven refractory materials and lithium technologies. Results of several Lewis studies are relevant to these technologies. For example, the long-term compatibility of these refractory alloys with high-temperature flowing lithium was demonstrated. Other studies include: the determination of long-term creep and thermal stability of refractory alloys; the preparation of specifications for obtaining refractory alloys qualified for lithium service; the fabrication of large-diameter refractory alloy pipe; the development of high-purity welding and joining techniques; the establishment of lithium handling and purification procedures; and the fabrication and operation of components for high-temperature lithium service, such as heat exchangers, pumps, valves, electric heaters and instrumentation. Some research related to evaluating the feasibility of fusion for propulsion may also be applied to ground fusion powerplant systems (50).

Another space technology which will have impact on the civilian sector is that of once-through boilers. The Environmental Protection Agency is pursuing the development of closed steam and organic-Rankine cycle engines for automobiles because of their potential for reduced emissions. These engines must satisfy stringent requirements on acceleration and other performance transients and must fit into a compartment not much different from that occupied by the internal combustion engine in today's cars. Most of the boilers for these auto engines are of the once-through type and several are adaptations of aerospace boiler designs. One major advantage of the once-through boiler over the recirculating type, for example, is its small working fluid inventory. Rapid engine startups and quick responses to operator demands are made possible by the small inventory. Moreover, in the event of a tube failure, the once-through boiler would discharge a smaller quantity of high temperature working fluid, an important safety feature. The compactness afforded by once-through boilers is, of course, another advantage of interest to the developers of these engines. Reference 51 illustrates the application of potassium once-through boiler design procedures developed under the space program to steam boilers for automobile engines.

The swirl-flow inserts developed for use in the potassium boiler may find application in the steam generators of liquid metal fast breeder reactor (LMFBR) powerplants. Reference 52 describes the design, fabrication and testing of a 1.5 MW_e capacity module of a sodium-heated steam evaporator proposed for this nuclear powerplant. The evaporator contains helical inserts to swirl the boiling flow. According to this reference, swirling the flow delays the onset of the departure from nucleate boiling (DNB) to higher qualities. Hence, thermal cycling of the tube wall separating the sodium and steam fluids will be held to a minimum by these inserts

resulting in greater reliability and longer life for the heat exchanger. Additional applications of the once-through boiler technology to non-aerospace uses should become evident in coming years.

The swelling of fuel clad and structural materials of the LMFBR is the subject of major effort by the Atomic Energy Commission. Excessive swelling would require premature fuel element removal, thus increasing the cost of electricity generated by the powerplant. Studies are being made of advanced LMFBR's using nitride, carbide and metallic fuels in place of the present uranium oxide. Also, alloys containing molybdenum, vanadium and niobium are being considered for cladding in place of stainless steels. Lewis' materials irradiation program for the space power reactor will obtain swelling data for some of these materials and fuels. This information should be very useful to breeder reactor designers.

In D-T fusion systems, very energetic neutrons at high flux levels will be formed and will interact with the plasma-containing walls. Neutrons of the spectrum and flux level believed typical of the fusion reactor cannot be generated either by reactors or ion accelerators. Consequently, engineering data on mechanical properties of materials irradiated under fusion reactor conditions may not become available prior to the construction of a fusion powerplant. The design of the containment wall and the selection of the material for this wall may well have to be predicated on a basic understanding of the swelling and damage mechanisms. Lewis' irradiation program, which is oriented toward obtaining a more fundamental understanding of these phenomena, represents another technology area of potential importance to the non-aerospace power generation field.

CONCLUDING REMARKS

This paper has presented a brief review of the two aerospace technologies being pursued at the Lewis Research Center. These two are directly relevant to the nation's capabilities to develop advanced terrestrial energy conversion systems, both stationary and mobile. They are providing means to improve the performance or service life of components for these systems and offer new ways of storing and transmitting energy. These technologies and their applications illustrate the relevance of aerospace technologies to other national needs.

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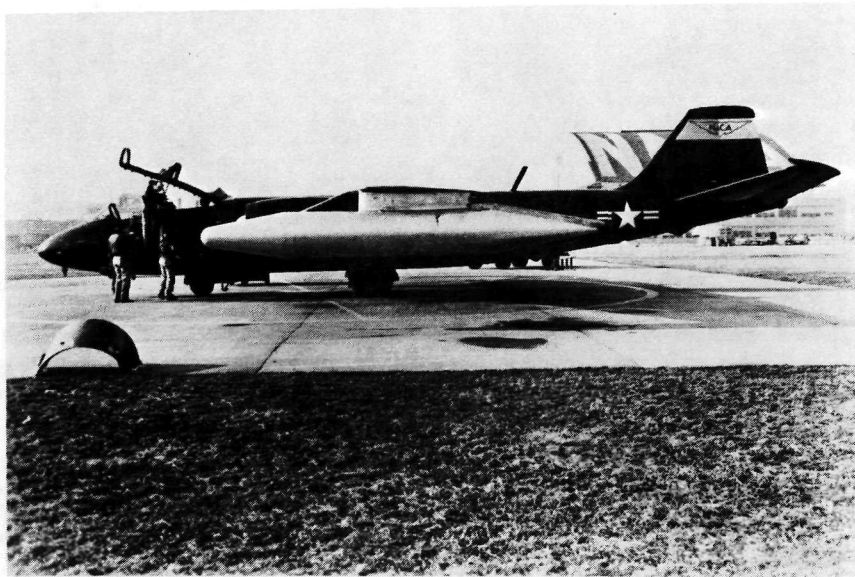


Figure 1. - NACA B-57 hydrogen-fueled aircraft.

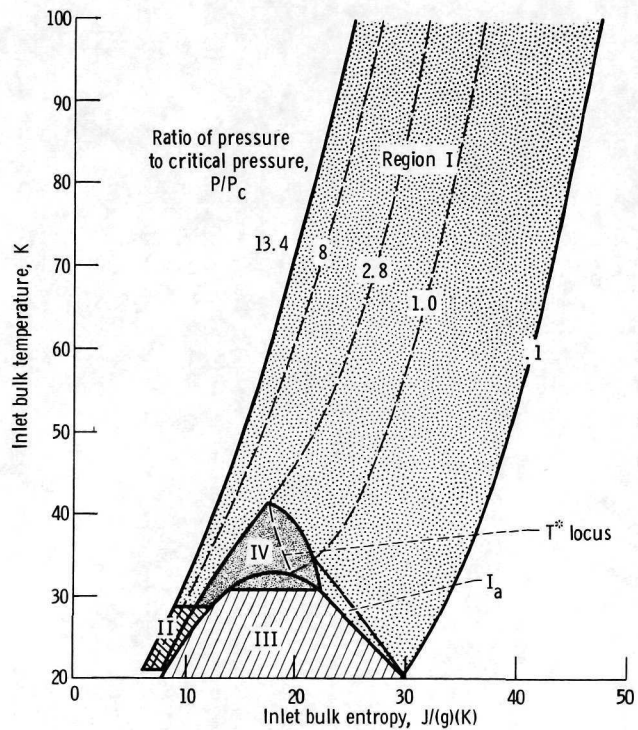
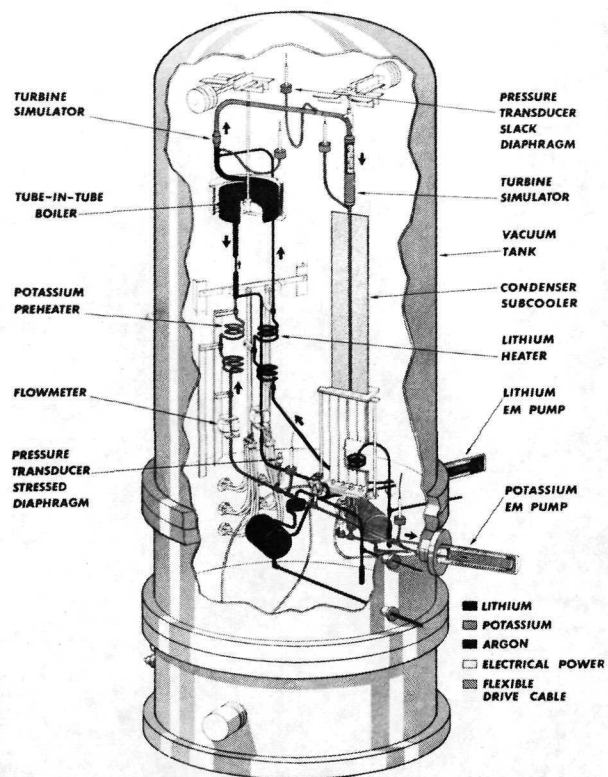


Figure 2. - Heat-transfer regions as function of inlet conditions. Region I, gas or fluid; region Ia, gas (low temperature); region II, liquid (fluid); region III, two phase; region IV, near critical.



CORROSION LOOP 1 [T-III]

Figure 3. - Schematic of refractory materials compatability test apparatus.

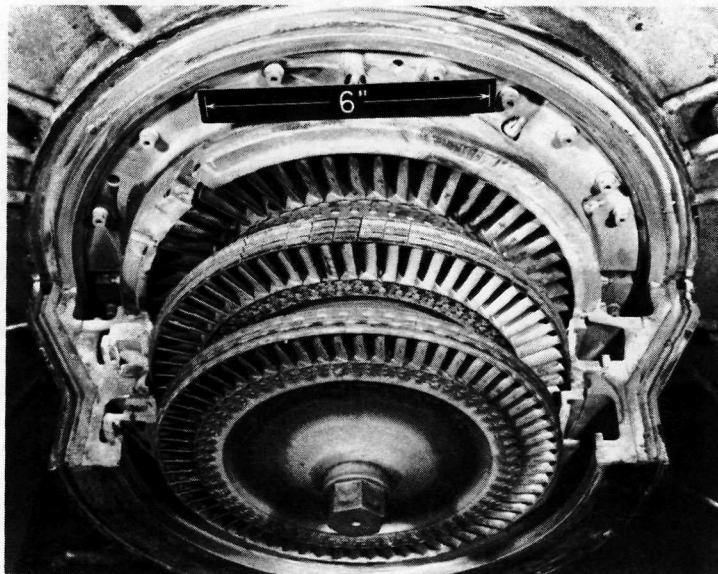


Figure 4. - Three stage potassium turbine after 5000 hours operation.

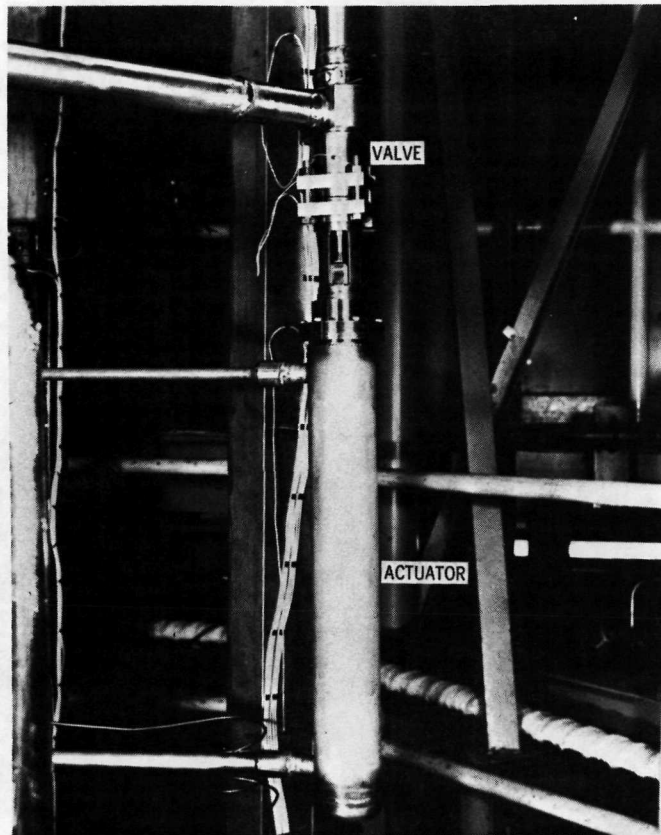


Figure 5. - Throttle valve for use with potassium.